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Simulation Programs for the L3+Cosmics Experiment

We present a collection of routines useful for simulating cosmic muons in the L3+Cosmics Experiment. They include code for generating muons, tracking them through the molasse and through the L3 setup. We define data formats for the data interchange between these programs.

1 Overview

In this note we give a short description of the following programs:

- CORSIKA — cosmic air shower simulation
- L3CGEN —fast muon generator
- TRACK —fast tracking through molasse
- SIL3C —complete L3+COSMICS detector simulation

The programs and utilities described can be found in directory `/pc/hub1c/data/l3cosmic/` on the L3 shift3 machine at CERN. Comments and error reports are welcome [1].

2 Shower simulation with CORSIKA

A program widely used for simulation of extensive air showers is CORSIKA [1]. It provides detailed information on shower content and development depending on the primary particle. The main drawback is the large amount of required computing time. The time to process one event strongly depends on primary type and energy.

primary energy	primary type	time per shower on HP735 excluding elm. cascades
500 TeV	iron	5 min
500 TeV	proton	3 min
5 TeV	proton	4 s

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2.1 Steering

A variety of options allow to customize the simulation. These options are set using a data card with switches.

Type, energy and angular range of the incident primary particle can be given via:

```
PRMPAR  14              ! primary type (proton)
ERANGE  2.00E4 4.00E6   ! energy range in GeV
THETAP  0.  10.         ! zenith angle range in degree
PHIP    0.  360.        ! azimuth angle range in degree
```

The energy of the primary is taken at random from a power law distribution inside the given intervall. The slope of the energy distribution can be defined using:

```
ESLOPE  -2.7  ! slope of energy spectrum
```

In the original CORSIKA version a lower limit of 80 GeV per nucleon exists. Protons are the only exception. The user can choose between different interaction models. Available models (VENUS, SYBILL, QGSJET, DPMJET) are descriped in detail in [1].

For the purpose of simulating muons underground the detailed simulation of the electromagnetic component is unnecessary. When these are swiched off via the flag:

```
ELMFLG T F
```

computing time is significantly reduced. For photon induced showers this option has to be switched on.

For a complete set of available switches we refer to the CORSIKA user's manual [2].

2.2 Installation

This is intended as a short introduction, for detailed information please refer to the user's manual. It is possible to obtain the CORSIKA code via ftp[2]. The version used so far is 5.20. The most recent version is 5.60.

The code is compatible with most systems. It has been succesfully installed on HP-UX and LINUX. The suitable options for these two systems are DEC-UNIX and LINUX. Objectfiles have to be made by invoking the FORTRAN compiler. For the LINUX version an additionally generated C–file has to be compiled with the C–compiler. The executable is created by:

```
f77 +E1 corsika_compilefile.f VENUS.o GHEISHA.o -o corsika.exe (HP-UX)
f77 corsika_compilefile.f VENUS.o GHEISHA.o TIMER.o -o corsika.exe (LINUX)
```

2.3 Output

Corsika writes every particle above an energy threshold that passes an observation level to the output file. The energy thresholds are defined by data card:

```
ECUTS  10.  10.  10.  10.  ! energy cuts in GeV (hadr. muon elec. phot.)
```

[2]Requests for ftp–access should be directed to <heck@ik3.fzk.de> or <knapp@ik1.fzk.de> by e–mail

Different observation levels can be specified by:
`OBSLEV 470E2` ! first observationlevel in cm
The coordinate system used has the z–axis up, x–axis to magnetic north and the y–axis to the west. Altitude of L3 surface level is 470m.

2.4 Utility programs

We provide a program `corread` to convert a CORSIKA output file into the /L3CEVT/ format used by L3+Cosmic programs. As this format contains only muons at ground level the filesize is reduced. This program also has a built in tiling mechanism, for better usage of MC statistics. This mechanism subdivides the shower area into squares of 50m length. The particle trajectories are extrapolated to a plane down in the depth of the L3 cavern parallel to the surface. The coordinates of particles in each square are then moved by the distance of the corrosponding square to the middle. That means that every 50m times 50m area is treated as an independent detector. This is aquivalent to smearing the shower axis with a fixed detector position [3].

The program `cors2gobi` is supplied to visualize the shower development. This program uses XGobi [4][5] as viewer and CORSIKA's plot version.

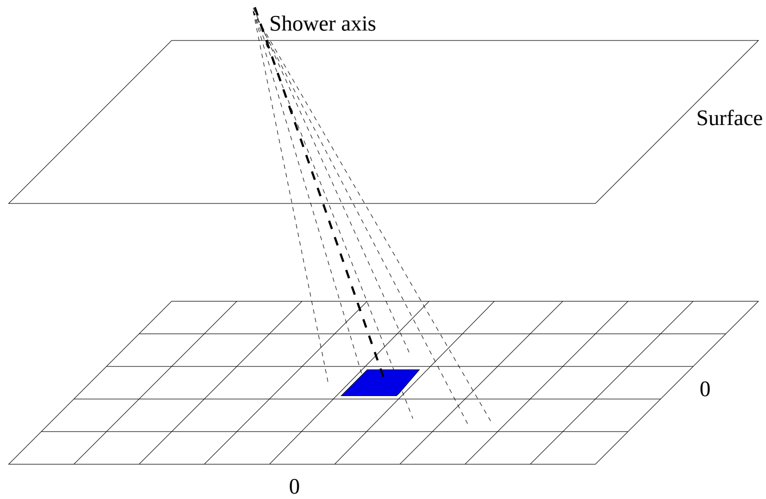

Figure 1: Only a few muons of a shower hit the detector situated at the origin.

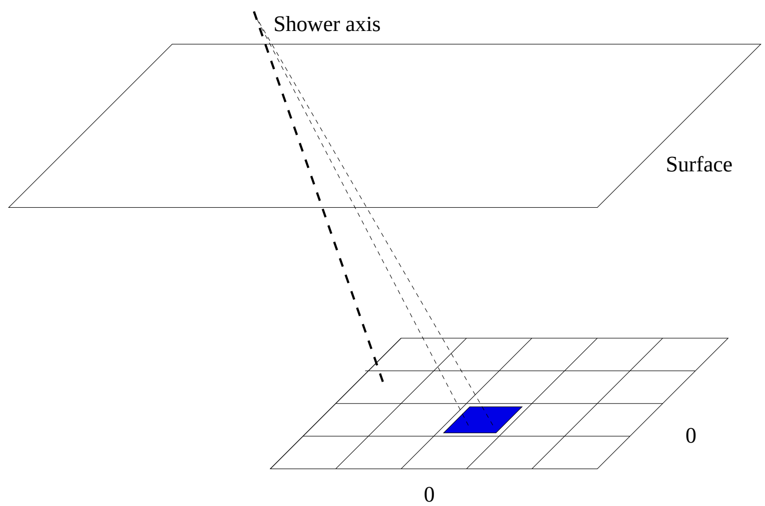

Figure 2: One of the subevents. The coordinate system has been moved.

3 The generator L3CGEN

Since CORSIKA is rather slow, it is necessary to build a simple muon generator based on a parameterization of the CORSIKA results.

The parameterization was obtained in the following way: CORSIKA 5.20 was used with default options to generate showers (Gheisha/Venus). Electromagnetic cascades were not simulated since they don't give muons. The zenith angle range was set to $\theta = 0 - 70$

degrees ($|\cos\theta| > 0.34$), the maximum permitted by CORSIKA. The energy distribution of the primary baryon hitting the atmosphere is assumed to fall $\sim 1/E_p^{2.7}$. As primary particles we considered protons (p), helium (He) and iron nuclei (Fe). Protons constitute the dominant component in the energy range of interest, iron represents heavy nuclei. To simulate the muon energy spectrum above a threshold of E_μ^* we must consider primary energies above a corresponding threshold E_p^*. It is chosen as the smallest number which fulfils: for $E_p < E_p^*$ muon energies are always below E_μ^*.
For protons we find approximately:

$$E_p^* \approx (1.5 - 3) \cdot E_\mu^* \tag{1}$$

where the bigger factor applies to small muon energies near 2 GeV and the smaller factor is valid for muon energy thresholds of a few 100 GeV. For p induced showers we generated muons down to energies of 2 GeV.
For iron:

$$E_p^* \approx 25 \cdot E_\mu^* \tag{2}$$

for $E_\mu^* > 200$ GeV. Since CORSIKA (in the standard configuration) cannot simulate iron showers below 5000 GeV, we were not able to obtain the corresponding muon energy and angular spectrum below $E_\mu = 200$ GeV. In the accessible energy range the muons originating from p, He and Fe look very similar, as figure 3 demonstrates for the energy and angular distributions. Therefore we finally used only p showers to determine the muon distributions.

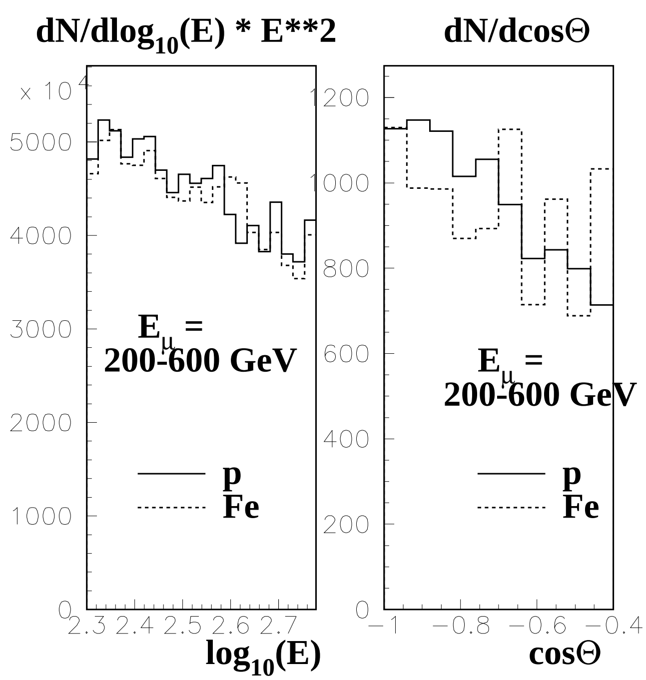

Figure 3:

The muons existing at an altitude of 470 m were written to a file and analysed later on. An absolute prediction of the primary or secondary flux is not provided by CORSIKA.

First we investigated the energy distribution integrated over the zenith angle range $|\cos\theta| > 0.4$. The value of $0.4 > 0.34$ was chosen to avoid 'edge effects'. Since the muon energy distribution falls off approximately as E_μ^3, we studied the distribution

$$E_\mu^2 \cdot \frac{dN}{d\log E_\mu} = \frac{dN}{d(1/E_\mu^2)} = E_\mu^3 \cdot \frac{dN}{dE_\mu} \tag{3}$$

which is flat for $dN/dE_\mu \sim 1/E_\mu^3$. The result shows figure 4. The shape can be parame-

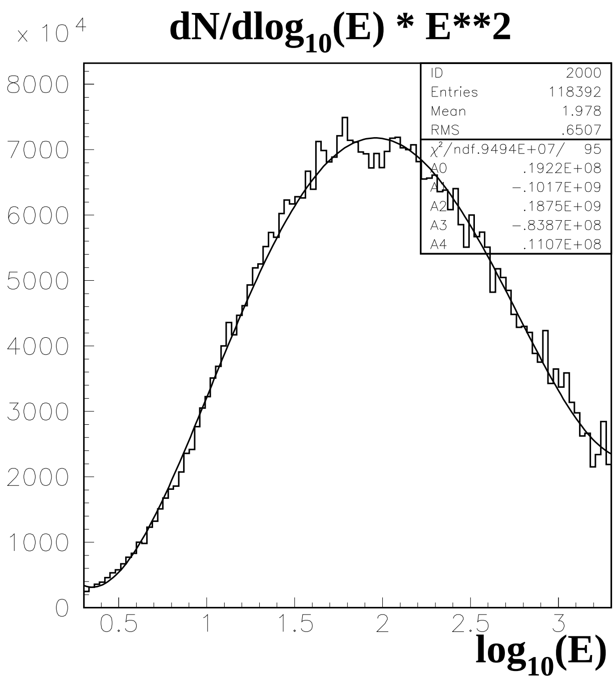

Figure 4:

terized by the polynomial

$$\sim 1.922 - 10.17 \cdot L + 18.75 \cdot L^2 - 8.387 \cdot L^3 + 1.107 \cdot L^4 \tag{4}$$

as demonstrated in the same figure. Here $L \equiv \log_{10}(E_\mu/\mathrm{GeV})$. Note that we plotted all muons produced in all showers, ignoring correlations within single showers.

Next we analyzed angular distributions as a function of muon energy. While the azimuthal angle has a flat distribution, the distribution of $\cos\theta$ is well represented by a linear function in $c \equiv \cos\theta$, see figure 5 (for muons near 17 GeV and for muon energies around 700 GeV):

$$\frac{dN}{dc} \sim 1 + a \cdot (1 - |c|) \tag{5}$$

The coefficient a is muon energy dependent (fig. 6). A good parameterization is

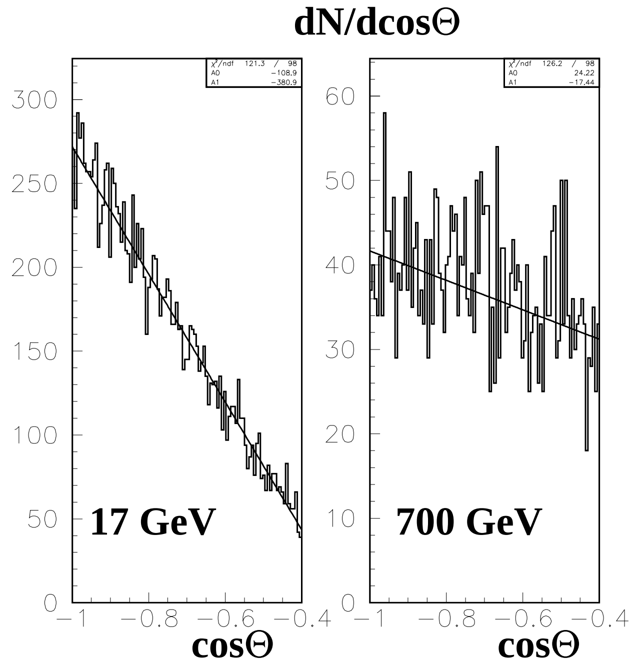

Figure 5:

$$a(l \equiv ln(E_\mu/\mathrm{GeV})) = -1.903 + 0.1434 \cdot l + 0.0145 \cdot l^2 \tag{6}$$

The distribution of the muon charge was not investigated in detail. There is no strong correlation to energy or angle. On average:

$$\frac{N^+}{N^-} = 1.3 \tag{7}$$

The FORTRAN program L3CGEN is based on these parameterizations. It allows to generate muons at the surface of the L3 site with a speed of up to 1 million events per minute on a HP735 workstation.
The muons are produced 'inclusively', which means that the program generates muons 'one by one' and does not deliver multi-muon events.
By counting the number of muons produced around 100 GeV, the generator can normalize with respect to the known flux of about

$$\frac{d\,N}{d\cos\theta\; d\,\phi\; dE\; d\,A} \approx 3 \cdot 10^{-3}\ /\mathrm{m}^2/\mathrm{s}/\mathrm{GeV}/\mathrm{sr} \tag{8}$$

and thus provide a relation between the number of generated events (for a given surface area) and the corresponding time interval.
Optionally the impact points at surface levels and the zenith angles can be constrained

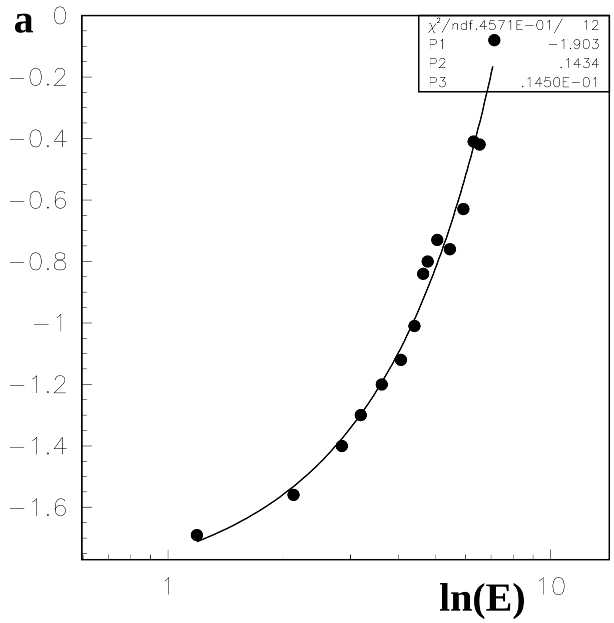

Figure 6:

such that the muons have a fair chance to reach the L3C setup (phase I or phase II). The selection is done conservatively: muons within the L3C acceptance are definitely not rejected.

The output format contains muon impact point, direction, energy and charge; it can be selected from a list of four options, see appendix. Among them is a ntuple (corresponding to common /L3CEVT/) and a packed binary file using only 8 Bytes per muon.

4 Tracking through molasse

For propagating muons from the surface down to the L3-Detector the program track3 is used. This program is based on GEANT [6]. The complete underground setup with all shafts is modelled. Surrounding molasse is approximated as a cone with a lower radius of 60 m and an opening angle of 60^o (see figure 4). The program is able to read different dataformats. It can read CORSIKA data, all L3CGEN formats. These dataformats are recognized using the file extension.

4.1 Installation

There exist two versions, one is interactive (mainly for debugging purpose), the other a batch version. For each version an install file is provided.

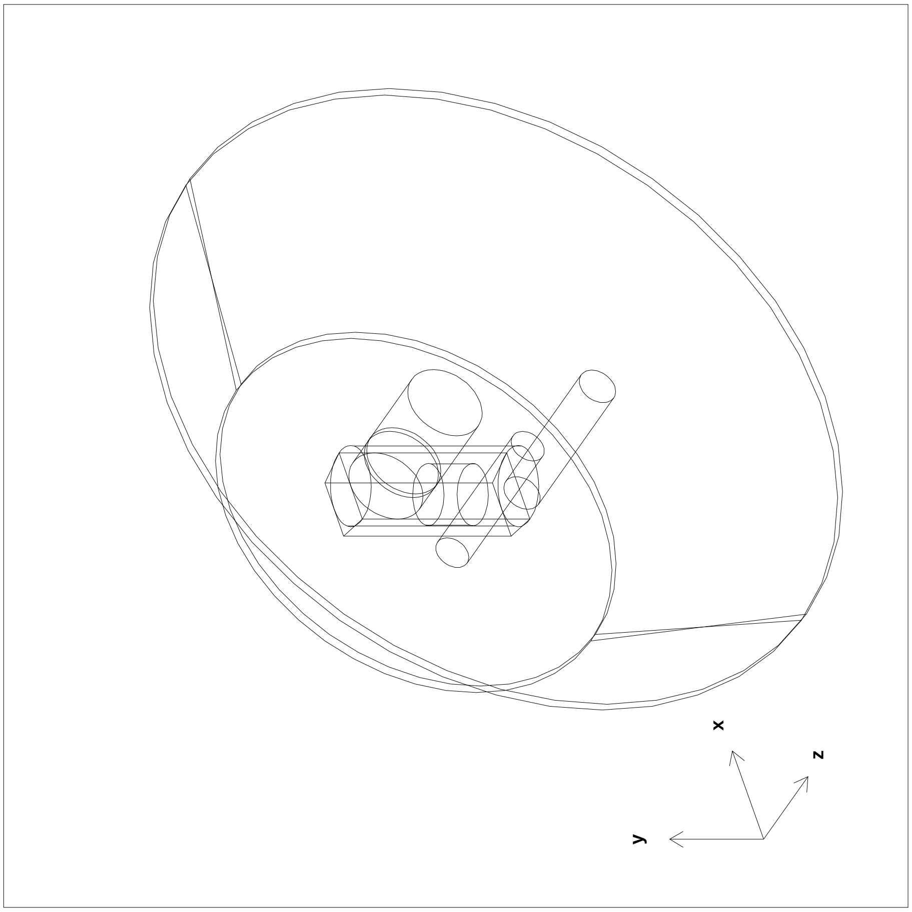

Figure 7: setup underground: Inside a cone of molasse three access shafts, the main hall and the LEP3 volume can be seen

All routines are stored in one CAR file.

4.2 Data cards

`SMEAR`	`T`	! enable smearing
`SELECT`	`T`	! enable selection
`REUSE`	`T`	! smear showers until they hit l3 requires SMEAR and SELECT
`EVOL`	`volume`	! stop volume TSCN, LEP3
`HBNM`	`filename`	! name of histogram file
`FINM`	`filename`	! name of input file
`FONM`	`filename`	! name of output file

SMEAR The shower axis is smeared in a circle of 140 m diameter. Without smearing the shower axis always goes through the origin.

SELECT If SELECT is enabled particles with an extrapolated hit position outside a circle of 16 m radius around the L3 vertex are not tracked.

REUSE REUSE smears the primary vertex again until a particle has a chance to hit the L3 volume. This option requires SMEAR and SELECT to be activated.

EVOL Particles are stopped at the borders of the specified volume. The two volumes are LEP3, a cylinder of 9.5 m radius and 14.2 m length and TSCN a box of 12.35 m x 6.35 m x 0.33 m around the t0 detector position.

FINM The name of the input file is specified. The program can read CORSIKA files and /L3CEVT/ formats. A CORSIKA file is assumed when the filename starts with 'DAT'. The /L3CEVT/ files are recognized via the file extensions '.l3c' and '.ntp'.

FONM This defines the output file path.

4.3 Output

The output contains the particle coordinates in the selected stop volume. Two possibilities can be enabled: The LEP3 volume, a cylinder of 9.5 m radius and 14.2 length and TSCN a box of 12.35 m x 6.35 m x 0.33 m. The particles are stopped at the borders of the volume. Output coordinates are L3 coordinates. The format used is described in chapter 6. If histogram output is selected the amount of matter traversed by the muon can be plotted.

5 L3+Cosmic detector simulation SIL3C

The detector simulation SIL3C is part of the cosmics analysis code COL3. This code is split into several `PATCHY` car files [7]. The most recent official version can be obtained from `/user/cosmic/col3` on the L3 HP–cluster at CERN.

The simulation includes the t0 detector and L3 setup. The complete underground geometry is present. Details on the detector simulation can be found in [8].

5.1 Installation

After unpacking the .tar file the execution of `col3/Install_Col3` creates necessary directory structures and builds the COL3 library.

The batch version is installed via `col3/v211/bin/install_l3c_simu`. Install file for the interactive version is `col3/v211/bin/install_l3c_simu_int`.

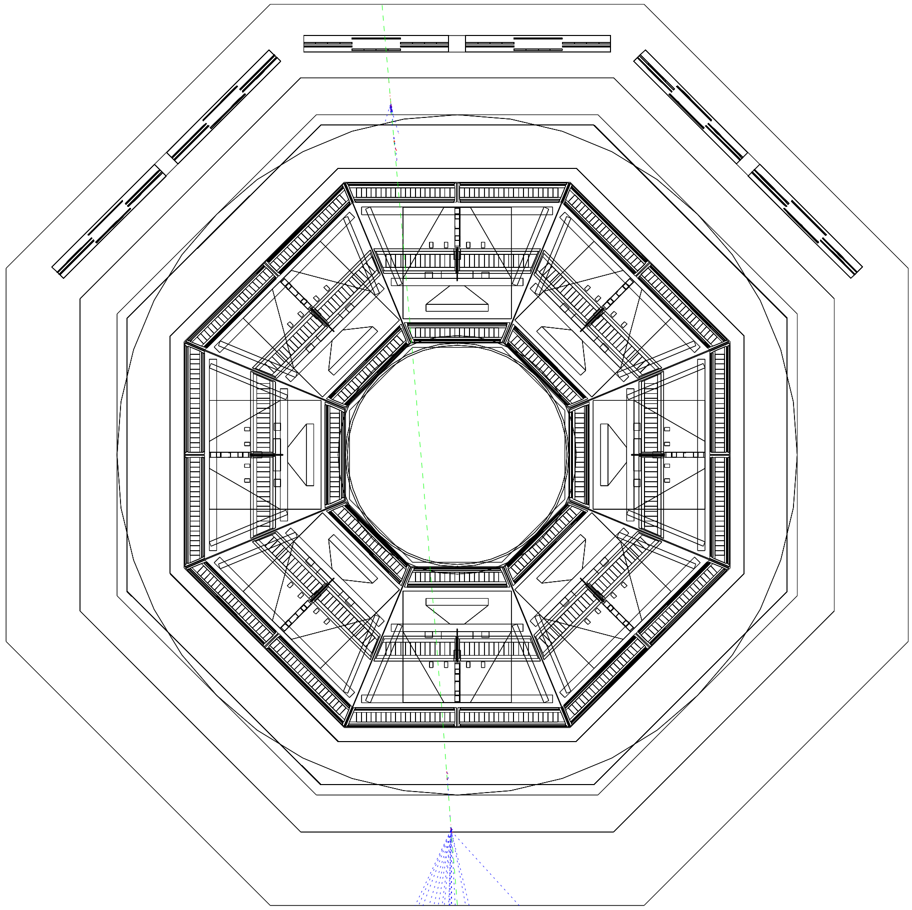

Figure 8: Simulated event of a 200 GeV muon passing the L3+Cosmics detector (Phase II). The structure inside the support tube is not drawn. At the bottom of the picture an electromagnetic shower generated in the iron yoke can be seen.

5.2 Data cards

The simulation is steered by a set of data cards. An example run file can be found at `col3/v211/bin/l3c_simu.run`. The complete list of available datacards is part of `utl3c.car` and `sil3c.car`. Only a subset can be described here.

`GEOM`	`volumekey parameter`	! volumes
`SETS`	`detectorkey parameter`	! detectors
`FLMP`	`filename`	! path to fieldmap
`IOPA`		! input/output
	`COSM`	! cosmic input
	`DAQC`	! output in new dataformat [9]
`DAQT`	`datetime`	! time for database
`CUTX`	`cutoff`	! cutoffs for special tracking media
`PHAS`	`phase`	! phase of L3C setup

```
DBL3                                ! path to database
        DBL3                        ! general database
        DBMU                        ! muon database
```

TRIG nevents Triggers a number of events.

GEOM volume parameter Specifies the volumes to be created. If the parameter is -1 the corresponding volume is not created. The default parameter is 3. There are three levels of volume keys :
1. 'LEP3'
2. 'xREG' for the 6 regions (x=T,E,H,F,M,A)
3. geometry keywords per REGion:
T region : 'TECH', 'TRBP' (xxBP stands for Beam Pipe structures)
E region : 'EBAR', 'ECAP', 'ERBP'
H region : 'HBAR', 'HCAP', 'HMFL', 'SBAR', SCAP'
F region : 'FCAP', 'FRBP', 'FQUA' (FQUA for quads. geometry)
M region : 'MBAR', 'MCAP', 'MGNT' (MGNT for magnet geometry)
A region : 'TSCN'

SETS detector parameter Specifies the detector response required. There are three levels of detector keys :
1. 'LEP3'
2. detector 'SCNT', 'MUCH', 'JTRG', 'TSCN'
3. subdetector keywords :
SCNT 'SBAR', 'SCAP'
MUCH 'MBAP', 'MBAZ'
JTRG 'JTMU', 'JTSC', 'JTL2', 'JTL3'
TSCN 'T0SC'

The parameter defines the appropriate action for the detector:
0 Nothing
1 Hits only
2 Hits and digitizations (default, may be omitted)
3 Hits, digitizations and noise

PHAS setup This defines the t0 scintillator setup to be used. For PHASE 1 $48m^2$ scintillator are created, PHASE 1.5 corresponds to $72m^2$ covered. Three scintillators of $72m^2$ are installed for PHASE 2.

FLMP filename Specifies the path to the magnetic field map for the yoke and coil region. Usually `col3/db/l3_50.map` is used.

IOPA key unit [chopt recordlength filename] Defines input and output files. If unit is negative optional parameters have to be given. The parameter chopt defines open parameters: Avalaible keys are:

COSM	input of cosmic events in /L3CEVT/ format
	chopt has to be 'LI' (C–library open for input)
GETY	input of standard generator events
DAQC	output of the new L3+COSMICS DAQ format [9]
	chopt has to be 'AO' (ASCII open for output)
	the new format requires wiring information from muon database
	A correct DAQ time has to be specified as well
SAVX	standard SIL3C output
HSTO	histogram output
	here the list of parameters is slightly different:
	unit chopt recl maxrec filename
	chopt has to be 'RO' (open random access output)
	maxrec gives the maximum filesize in records

DBL3 key unit [recl maxr chopt dopt] vers filename Defines database to use. Allowed keys are 'DBL3', 'DBMU', 'DBSC' and 'DBJT'. The database is specified by version and filename. If the unit is negative some additonal parameters have to be given. The first parameters are recordlength and maximum file size. The next two are options for file and database opening (e.g. 'R' and ' ').

DAQT yymmdd hhmmss Sets DAQ time of the event. The DAQ time is needed to access the correct database information.

CUTX parameter Kinetic energy cuts in special tracking media on (X=E,G,H,M,N) electrons, gammas, hadrons, muons and neutrons. For each medium a parameter is needed:

1 — gas in TEC
2 — special air
3 — Brass
4 — gas in HCAL/FWCH
5 — gas in Mu-P chamber
6 — gas in Mu-Z chamber
7 — Uranium mixture
8 — RPC Gas
9 — Gas in FB Mu-chamber
10 — Aluminium

11 — Iron
12 — Molasse above L3

5.3 Interactive simulation commands

The interactive simulation is mainly useful for test purposes. As user interface KUIP is used. An online help mechanism can be invoked with `HELP`. Here is a short list of useful commands:

DTREE volume level Draws the tree of volumes up to the specified level.

DSPEC volume Displays volume specifications. Used parameters are printed and all 3 projections drawn.

SCALE xscale yscale Changes the drawing scale.

DRAW volume [theta phi psi u0 v0 su sv] Draws a volume. Drawn is a projection under viewing angles theta and phi rotated by psi. Additional offset and scale factors can be given.

NEXT Clears the graphic window.

KINE ikine parameter Defines kinematics of an event. For ikine = 1 a single particle is generated. Needed parameters are particle type, incident angle theta and phi, energy and three vertex coordinates. Only active if GETY and COSM are not used.

TRIG nevents Triggers a number of events.

DXYZ Draw particle trajectories.
Dotted blue —gammas
Dashed green —muons
Solid red —other charged particles
Dotted black —neutral hadrons and neutrinos

DHITS Draws hits.

DAXIS xo yo zo size Draw mother coordinate system axis at (xo,yo,zo). The fourth parameter specifies the length drawn.

PHITS Prints hit specifications.

PDIGI Prints digitisations.

6 Data format and Interface library

The underlying data structure used for data interchange is based on the /L3CEVT/ common block. This structure is inspired by the HEP common [10]. The common /L3CEVT/ contains the output variables for one event:

nevl3c	event number (1,2,3,....)
nshl3c	shower number producing this event(e.g. CORSIKA event nr.)
nrul3c	run number (e.g. CORSIKA run nr.)
ndal3c	Modified Julian date (Universal Time) (50814 - ...)
timl3c	day time, fraction of a day (Universal Time) (0 ... 0.99999..)
	time = time of impact of primary particle on atmosphere
idpl3c	identifier of primary particle impinging on atmosphere
	following jetset standard, e.g. proton = 2212
ppl3c(4)	4 momentum of primary particle:
	ppl3c(1) = x momentum component = px/ptot (-1 ... 1)
	ppl3c(2) = y momentum component = py/ptot (-1 ... 1)
	ppl3c(3) = z momentum component = pz/ptot (-1 ... 1)
	ppl3c(4) = energy in GeV
	(L3 coordinate system)
vpl3c(4)	impact point/time of primary particle (in upper atmosphere):
	vpl3c(1) = x coordinate in m
	vpl3c(2) = y coordinate in m
	vpl3c(3) = z coordinate in m
	vpl3c(4) = time difference of impact with respect to timl3c in s
	(normally 0 !)
	(L3 coordinate system)
nl3c	number of secondaries arriving at surface of earth (here: 1)
ipl3c(..)	identifier of secondary particle
	following jetset standard muon = 13, antimuon = -13
pl3c(4,..)	4 momentum of secondary particle:
	pl3c(1) = x momentum component = px/ptot (-1 ... 1)
	pl3c(2) = y momentum component = py/ptot (-1 ... 1)
	pl3c(3) = z momentum component = pz/ptot (-1 ... 1)
	pl3c(4) = energy in GeV (2 ...)
	(L3 coordinate system)
vpl3c(4,..)	impact point/time of secondary (surface):
	vl3c(1) = x coordinate in m
	vl3c(2) = y coordinate in m

vl3c(3) = z coordinate in m
vl3c(4) = time difference of impact with respect to timl3 in s
(L3 coordinate system)

Optional it is possible to use the same common block for header information, flagged by a negative event number nevl3c. Typically there is one such block per file (e.g. at the beginning)

nevl3c	-1
ndal3c	date of generation (s. above)
timl3c	version (and revision number) of program producing file (e.g. generator, e.g. version 2.7)
idpl3c	program code: 101 = corread 202 = l3cgen2 301 = track
ppl3c,	program dependent parameters
vpl3c	here: ppl3c(1) = ntot, ppl3c(2) = emin, ppl3c(3)=igeom

For input/output we provide the library `l3cout`. This library provides a collection of routines to read and write the /L3CEVT/ structure to disk. A C–style file format based on the CFIO package of CERNLIB (Z310) is used.

Files are opened with a call to `OPENC`. The returned value for the file descriptor LUN has to be used in all other calls. As status variable IERR is returned. After succesfull execution it is set to zero. Normally files are written via `WRITEL3CEVT` and read by `READL3CEVT`. To read the compressed MINI format optionally written by L3CGEN the routine `READL3M` has to be called. As an option the information is read from integer variables INT1 and INT2 and not from a file, if LUN is zero.

Routines in `l3cout`

```
c        OPENC(LUN,FNAME,IERR)
c        WRITEL3CEVT(LUN,IERR)
c        READL3CEVT(LUN,IERR)
c        READL3M(LUN,INT1,INT2,IERR)
c        PUTWORD(LUN,WORD,IERR)
c        WRITEREAL(LUN,RWORD,IERR)
c        WRITEINT(LUN,IWORD,IERR)
c        GETWORD(LUN,WORD,IERR)
c        READREAL(LUN,RWORD,IERR)
c        READINT(LUN,IWORD,IERR)
```

7 Acknowledgements

The members of the Nijmegen COL3 programming team A. van Mil, B.Petersen, H. Wilkens contributed greatly to TRACK and SIL3C. For providing CORSIKA we would like to thank D. Heck and J. Knapp.

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